ASSESSMENT OF COMMUTING UNDER GRADE LOADS AND RAMP METERING: PRELIMINARY ON-ROAD EMISSIONS FINDINGS

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ABSTRACT

This project was developed to assess driving patterns likely to promote emission excursions greater than those encountered in current dynamometer driving cycles. The strategy involved three phases: the use of an instrumented vehicle to measure on-board emissions; the use of an instrumented vehicle to develop ramp driving cycles; and the dynamometer testing of 10 vehicles on a simulated ramp, both metered and unmetered.

The first phase showed that on average the emission effects are exacerbated with a fully occupied vehicle (4 passengers) while driving on a hill (4.5% grade) by a factor of 2, both for hydrocarbons and CO. A simulation was performed for a trip of 10 miles with a hill (3% grade) of the same length of Bag1 of the Federal Test Procedure to assess the effects on commute trips (including cold starts).

The second phase focused on developing two cycles that simulate an on-ramp. The RAMP1 cycle was develop to simulate free flow entering an on-ramp and RAMP2 was developed to simulate a metered flow entering the same on-ramp. Both cycles have the same distance and include three subcycles representing the simulated ramp. Each subcycle has 3 distance-based modes: on-ramp, merging, and the remainder of the cycle. These subcycles included accelerations up to 4.8 MPH/second for RAMP1 and up to 6.3 MPH/second for RAMP2.

Finally, the third phase included the testing of 2 carbureted and 8 fuel injected vehicles, ranging from 1976 to 1992 model year on the RAMP1 and RAMP2 cycles. Preliminary findings indicate incremental emitting potential of metered ramps of 0.28 grams/event for hydrocarbons, 4.8 grams/event for CO, and 0.09 grams/event for NO_x. These events correspond roughly to 10% to 20% of the incremental cold start emissions (approximated as Bag 1 minus Bag 3) of the FTP for this particular fleet.

The results highlight the importance of including emissions caused by high load events not accounted for in the current mobile source emissions inventory.

INTRODUCTION

Dynamometer testing has shown that significant emissions excursions occur due to hard accelerations[1,2], particularly when going from low speed to speeds exceeding 45 MPH. Additionally, driving on grades also increases exhaust emissions[3,4,5,6]. Conditions like this are commonly encountered on on-ramps, and may be exacerbated when the merging distance is short or the ramp has a positive grade.

The United States Environmental Protection Agency (EPA)[3] stated that the nationwide vehicle-miles traveled weighted average for road gradient is 1.6%. This figure assumes that the positive grade miles are equal to the negative grade miles. A number of studies have shown that driving on positive gradients, namely on hills[4,5,6], or in tunnels[7], increases exhaust emissions. A recent study[6] developed by this research team assessed driving patterns on road grades that promote emission excursions. An instrumented vehicle was equipped to record driving conditions such as speed and grade, as well emission rates of hydrocarbons and carbon monoxide (CO). Controlled runs with predetermined cruises and accelerations were conducted on flat terrain and on hills with grades ranging from 0% to 7%. The hills were located in metropolitan Los Angeles, both on freeways and arterials. For hydrocarbons, the increase in emissions was about 0.04 g/mile for each 1% grade increment. The case of CO was more dramatic with an increase of 3.0 g/mile for each 1% grade increment. For a fully occupied vehicle with 4 passengers on a 4.5% grade, emissions increased by 0.07 g/mile for hydrocarbons and 10.2 g/mile for CO. Air conditioning operation, at full setting, further increased emissions while driving on hills (4.5 and 6.7% grades): 0.07 g/mile for hydrocarbons and 31.9 g/mile for CO.

Other places that may promote emissions excursions include ramps where hard accelerations plus grade effects may interact. Ramps have varied designs[8] including the following factors: curvature, length, auxiliary lanes, grades, and metering which may include different queue and merging lengths, or the presence of a dedicated carpool lane. Additional factors that may affect the operation of vehicles on ramps include the activity within the merging of the main traffic flow and the vehicle idle time and related creep while entering the freeway. A study by Sullivan[8] examined the speed distributions of vehicles entering ramps using a video camera. The operator of the camera followed vehicles on the ramp and later calculated the speed by viewing the videotape and measuring the time required for the vehicles to travel between reference cones. However, this study was inconclusive concerning the potential impact of ramp metering on air quality. During 1994, the Delaware Valley Regional Planning Commission released a study[9] on transportation control measures (TCM) that also contemplated ramp metering. The Delaware's study presented expected emission benefits due to improvements on flow conditions, concluding that "this TCM would result in an average increase in speeds of 6 MPH."

COMMUTING UNDER GRADE LOADS (1 vehicle)

As mentioned before, an instrumented vehicle was used to assess the effects of grades, passengers and air conditioning loads on exhaust emissions[6]. In the study Federal Test Procedure test were performed and basic emission rates were developed including incremental rates for cold starts (Bag 1 minus Bag 3), and speed specific rates were calculated using the speed correction factors used in EMFAC7F. The emission rates measured by the instrumented vehicle are presented in Table 1.

Implications for Evaluating Transportation Control Measures

The present study suggests that some transportation control measures (TCMs) designed, in part, to improve air quality may actually result in increased exhaust emissions for individual trips. For these cases, it is important to evaluate the effectiveness of carpooling in terms of emission rates per carpool occupant. As discussed above, our data show that vehicle emission rates are significantly increased when the vehicle is fully occupied and driven under certain high load conditions, such as on a hill. This suggests that high occupancy vehicles (HOVs) may have a lesser effect on improving air quality than has been commonly assumed in air quality management plans in which significant tons per day credits for CO and hydrocarbons have been given to such TCM.

Table 1. Grade and associated effects on emissions.

HC			
	Speed	0.08 g/mile	at 30 mph
	Cold Start	0.42 g/mile	for 3.6 miles
	Grade	0.12 g/mile	for a 3% grade
	AC	0.08 g/mile	while operating (on-grades)
	Full Occupancy	0.07 g/mile	4 passengers (on-grades)
CO			
	Speed	1.9 g/mile	at 30 mph
	Cold Start	3.0 g/mile	for 3.6 miles
	Grade	9.0 g/mile	for a 3% grade
	AC	32.9 g/mile	while operating (on-grades)
	Full Occupancy	10.2 g/mile	4 passengers (on-grades)

To calculate the benefits of person trips avoided, a scenario for multiple carpool occupants was evaluated. The scenario assumed a trip of 10 miles that included a hill with a positive grade of 3% for 3.6 miles, and included a cold start. First, the emission rates per occupant were calculated assuming only the incremental emissions from a cold start and emissions from the 10 mile distance trip at 30 MPH assuming the basic emission rates given by current modeling assumptions (eg. EMFAC7F). Additionally, emissions due to grade and full occupancy (when pertinent) were included to assess the effectiveness of carpooling for hilly areas. Table 2 presents the modeling assumptions. The results of this analysis are presented in Table 3. Hydrocarbons emission rates expressed as g/mile did not vary significantly between current modeling and modeling incorporating grade and vehicle occupancy. However, this analysis indicates that grade and full occupancy increases CO emission rates by a factor of three for a fully occupied vehicle, and by a factor of two for lower vehicle occupancy when compared to current modeling. A fully occupied vehicle emits 20% less CO per occupant than the same vehicle with 2 passengers, but 19% more per occupant than with 3 passengers.

High occupancy vehicles (HOVs), while operating in hilly terrain, may have a lesser effect on improving air quality than has been commonly assumed. Other potential beneficial effects of HOV lanes were not considered in this analysis, such as reduced traffic congestion. The effects may become more pronounced for larger grades and additional vehicle occupants, and points to the importance of evaluating TCM's based on technical information.

Table 2. Carpooling efficacy, modeling assumption scenario with and without a hill.

speed	30 MPH
total distance	10 miles
cold start	yes
hill grade	3%
hill distance	3.6 miles
occupancy	1,2,3 and 4 passengers

Table 3. Modeled results for high vehicle occupancy with and without a hill.

number of occupants	emission rate (g/mile/passenger) without-hill 0% grade	with-hill 3% grade
HC		
1	0.23	0.27
2	0.11	0.14
3	0.08	0.09
4	0.06	0.08
CO		
1	3.01	6.25
2	1.51	3.12
3	1.00	2.08
4	0.75	2.48

RAMP CYCLE DEVELOPMENT (1 Vehicle)

The cycles were developed from routes driven by an instrumented vehicle. The vehicle was equipped with an on-board datalogger capable of measuring basic driving parameters, such as speed. Uncontrolled runs on metered and unmetered ramps were conducted on three different types of ramps on the Santa Monica Freeway (I-10) in Los Angeles. The first was a positive grade with metering at the end of the ramp (Centinela or Bundy Avenues, east-bound). The second was a negative grade with metering at the end of the ramp (Overland Avenue, east-bound). The third one was a positive grade with metering at the middle of the ramp (Robertson Boulevard, west-bound). The runs were driven at the same speed as the traffic or when there was no traffic, in the "driving style of the driver". The experiments were performed between October 21 to October 25, 1994 between the times of 6:00 am to 6:00 pm. Ramp metering was in effect for the entire test period with the exception of the time prior to 7 am for the second ramp. Due to the availability of both free flow and metered conditions, the second ramp was selected to develop the metered and unmetered ramp driving cycles for a "typical" morning commute speed-time profile.

The ramp selected has a distance of 0.21 miles, including the portion of the ramp prior to the metering light and the queue to enter the ramp. The merging segment of the ramp includes a distance of 0.38 miles from the metering light to the point on the freeway where traffic travels at average freeway speeds. The remaining 1.55 miles of the trip includes a "cruising" at freeway speed and the exit at the next off-ramp, with a total distance of 2.14 miles. From the driving patterns observed, 6 trips were selected (3 unmetered and 3 metered). These trips were included as 3 subcycles in the main cycles separated by 45 seconds intervals (20 seconds at the end of each subcycle and 25 seconds at the beginning) for a total distance of 6.43 miles. The RAMP1 cycle was developed to simulate free flow conditions entering this on-ramp and RAMP2 was developed to simulate metered flow entering the same on-ramp. These subcycles included accelerations up to 4.8 MPH/second for RAMP1 and up to 6.3 MPH/second for RAMP2. Figure 1 presents the time-speed profiles, and Figure 2 the distance-speed profiles of the cycles. For the RAMP1 cycle, in Figure 2, a smooth transition from the ramp to the main flow merging occurs at approximately 55 MPH. In contrast, RAMP2 shows two well defined modes for entering the ramp and stopping at the meter containing multiple microtrips, and a subsequent acceleration event to reach the merging speed at a cruise around 50 MPH.

Table 4. Cycle, subcycle and ramp length.

Cycle (includes 3 ramps)	6.43 miles
Subcycle (includes 1 ramp)	2.14 miles
on-ramp	0.21 miles
merging	0.38 miles
remaining trip	1.55 miles

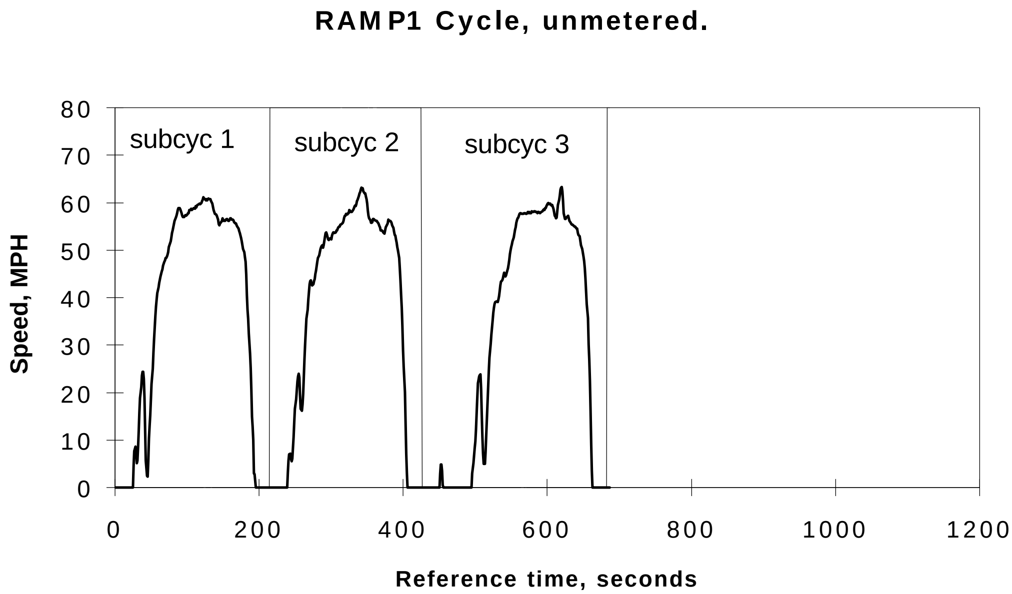
Table 5. Basic statistics of ramp1 and ramp2 cycles.

	duration (seconds)	average speed	average running speed (mph)	max speed	max accel (mph/s)	idle (%)
RAMP1 un-metered	682	33.9	45.6	63.3	4.8	25.7
RAMP2 metered	1073	21.5	28.4	67.0	6.3	24.1

DYNAMOMETER TESTING OF A RAMP, METERED AND UNMETERED (10 Vehicles).

Of the ten vehicles evaluated, six were 1992 model year, two 1989 model year, and the remaining two carbureted vehicles of 1976 and 1982 model years. Table 6 presents a brief description of the test fleet including: manufacturer, model, engine size, transmission type, inertia weight and odometer reading

Figure 1. Time-speed profiles for RAMP1 and RAMP2 cycles and subcycles.



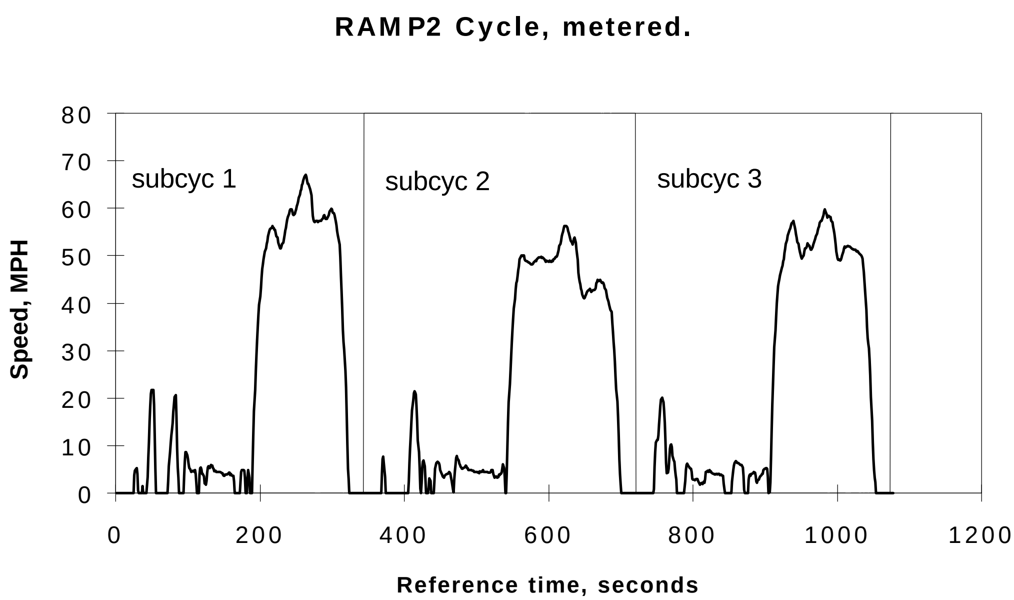
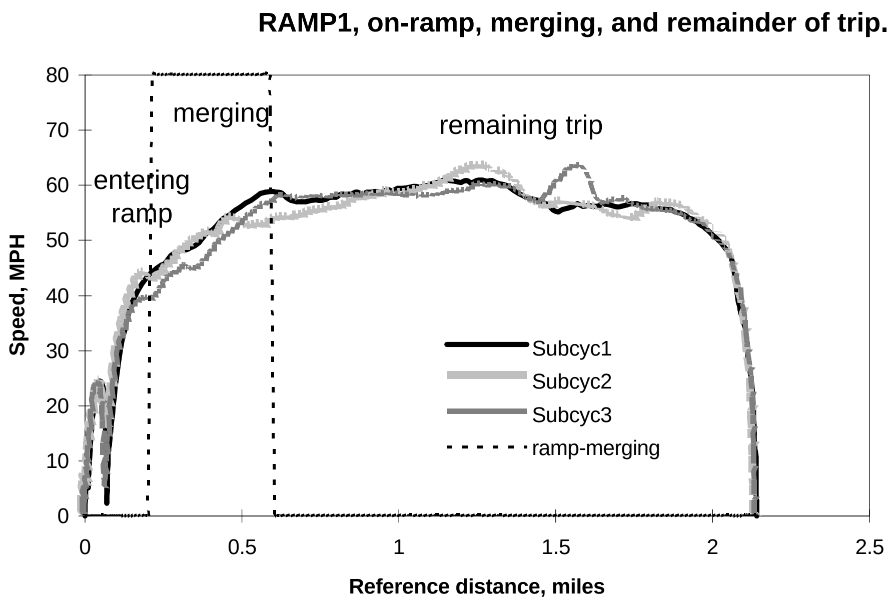


Figure 2. Distance-speed profiles for RAMP1 and RAMP2 subcycles and modes.



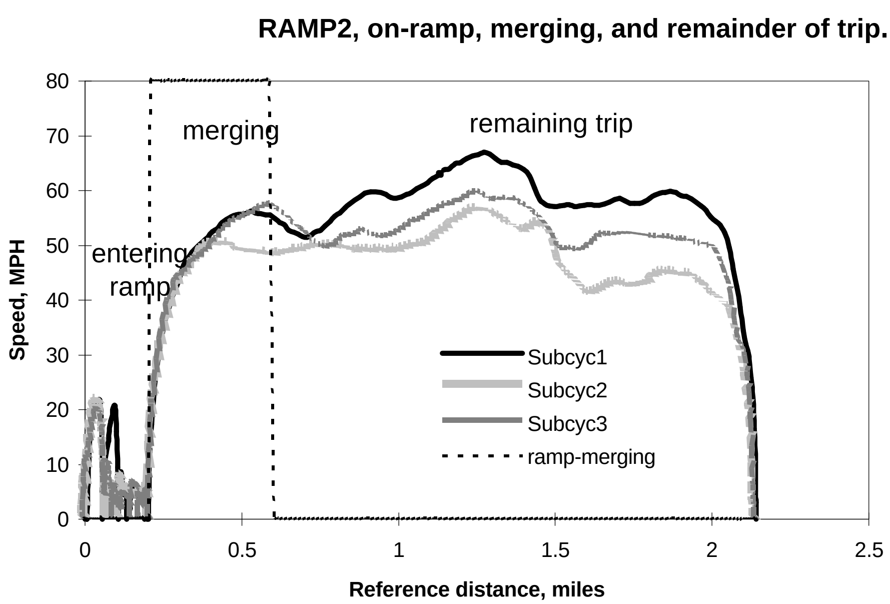


Table 6. Test Fleet.

	Year,	Manufacturer & Model		Engine Size (L)	Fuel System
1	1992	Ford	Taurus	3.0	F. Inj.
2	1992	Ford	Tempo	2.3	F. Inj.
3	1992	GM	Granada	2.3	F. Inj.
4	1992	Honda	Accord	2.2	F. Inj.
5	1992	GM	Astrovan	4.3	F. Inj.
6	1982	Toyota	Celica	2.4	Carbu.
7	1976	Ford	Monarch	4.1	Carbu.
8	1989	GM	Sedanville	4.5	F. Inj.
9	1992	GM	Lumina	3.1	F. Inj.
10	1989	Honda	Civic	1.5	F. Inj.

A hydrokinetic dynamometer manufactured by Clayton (model CPE-50) was used for the testing. The CVS (constant volume sampler) unit and analysis train consisted of the following Horiba models: PIR-2000 for CO and CO_2; OPE-315 for O_2; OPE 435 for HC; and OPE-235 for NO_x. Second-by-second concentrations were measured from the vehicle exhaust emissions. Bulk summertime fuel was used for all of the testing. The vehicles were tested on five cycles: a standard Federal Test Procedure (FTP), the Unified Cycle[10] (UC), the CARB Acceleration Cycle[1] (ACCEL1) and two specially designed cycles that simulate an on-ramp, RAMP1 and RAMP2.

Baseline Emissions

As expected, under FTP conditions the newer vehicles were relatively clean with a few exceptions. On average hydrocarbons were 0.57 g/mile, CO emissions were 8.0 g/mile and NO_x emissions were 0.94 g/mile, but the older vehicles produced higher emissions. All pollutants showed very high variability (coefficient of variation, ranging from 80% to 129%). Table 7 presents a summary of the average, standard deviation and coefficient of variation for the test cycle emission rates. Table 8 presents the results of the test cycles by vehicle. Figure 3 shows the emission rates for the fuel injected and carbureted vehicles. For the ACCEL1 cycle, newer fuel injected vehicles have a higher average value for CO, close to 80 g/mile in contrast to 25 g/mile for carbureted vehicles. The carbureted vehicles present similar emissions under FTP conditions than under the ACCEL1 cycle, implying a consistent rich operation. The high emissions in newer cars reflects "open-loop" or "fuel enrichment" events occurring in current technology vehicles. These results for fuel injected vehicles are consistent with previously reported data[1,2] using the same cycle. In terms of distance-based emission rates, the metered ramp cycle (RAMP2) shows hydrocarbons and CO emissions more than 50% higher than its non-metered counterpart (RAMP1). In the case of NO_x, RAMP1 has slightly higher emissions than RAMP2, likely due to hydrocarbons and CO tradeoff with NO_x.

Analysis by Cycles and Modes (2 Cycles x 3 Subcycles x 3 Modes)

As previously mentioned, each cycle is divided into 3 subcycles, each subdivided into 3 modes. The first includes the on ramp up to the metering light and the queue to enter the ramp, if any. The subsequent mode includes the portion of the ramp from the metering light to the point of average speed of the main flow on the freeway. Finally, the remainder of the trip includes cruising at freeway speed and the exit at the next off-ramp. Using these 3 modes, their total emissions were calculated using second-by-second data. A total of 60 observations were generated per cycle (10 vehicles, 2 replicates, and 3 subcycles). Figure 4 presents the total emissions by mode. When entering the ramp, hydrocarbons and CO are higher for RAMP2 than for RAMP1, although the difference is not statistically significant. A similar pattern occurs for the merging portion but in this case the difference between metered and unmetered ramps is significant for these two pollutants. For the remainder of the trip, the total emissions are very similar. In contrast, for NO_x the free flow mode has higher emissions (with a statistically significant difference), than the metered mode, most likely due to higher speeds and kinetic energy. For merging, the metered mode is higher than the unmetered one, although with a statistically insignificant difference. The remainder of the trip resulted in higher emission for the nonmetered cycle, the higher emissions most likely due to higher speeds.

When combining the entering and merging portions of the ramps, the differences between the metered and unmetered cycles becomes more apparent. For hydrocarbons the metered ramp produced 110% more emissions per event than the unmetered cycle. In the case of CO the metered ramp produced 90% more emissions than the unmetered ramp. For both pollutants, hydrocarbons and CO, the differences were statistically significant. In the case of NO_x the difference was marginal, the metered cycle being 9% higher than the unmetered cycle and statistically insignificant. The incremental emitting potential of metered ramps is 0.28 grams per event for hydrocarbons, 4.8 grams per event for CO, and 0.09 grams per event for NO_x. When the total incremental grams per event are calculated they correspond roughly to 10% to 20% of the incremental cold start emissions calculated from the difference between Bag 1 and Bag 3 of the FTP, as shown in Table 7.

Implications for Ramp Metering and Trip Length

Using EMFACT7F speed correction factors and the measured emissions of the test fleet used in this study, the necessary change in of speed to overcome the incremental emissions due to ramp metering was calculated. For this purpose, three trip lengths were used: 3.0 miles, 4.3 miles, and 8.6 miles. These distances correspond to the first, second and third quartile of trips including ramps from the data collected during the "Characterization of Driving Patterns and Emissions from Light-Duty Vehicles in California"[11] during 1992. The current speed correction factor functions have a minimum which varies depending on the pollutant. The minimum speed correction factors occur at 52.0 MPH for hydrocarbons, 42.8 MPH for CO, and 32.0 MPH for NO_x. Above these speeds, there is no apparent air quality benefit for ramp metering. The results for the 3 different length trip scenarios are presented in Table 9. The short and medium length trips require enhancement of speeds ranging from 12.5 MPH to 18.5 MPH to offset the emissions due to the metered ramp condition for hydrocarbons and CO. These speed enhancements are unlikely according to the estimates developed for Delaware[9]. For the longer trip, the speed enhancement should be 7.8 MPH for hydrocarbons, 11.4 MPH for CO, and 4.0 MPH for NO_x.

Table 7. Test cycles emission rates (from bag samples).

	n	HC grams/mile Avrg.	HC grams/mile S. Dev.	HC grams/mile COV	CO grams/mile Avrg.	CO grams/mile S. Dev.	CO grams/mile COV	NOx grams/mile Avrg.	NOx grams/mile S. Dev.	NOx grams/mile COV
FTP	10	0.57	0.45	80%	8.0	8.5	106%	0.94	1.22	129%
Bag 1	10	1.00	0.52	52%	12.2	9.6	78%	1.36	1.47	108%
Bag 2	10	0.47	0.54	115%	7.8	11.0	141%	0.69	0.90	131%
Bag 3	10	0.42	0.34	80%	5.4	4.5	84%	1.11	1.67	151%
UC	10	0.48	0.37	78%	8.5	6.3	74%	1.22	1.75	143%
Bag 1	10	2.47	0.95	39%	28.7	22.3	78%	2.17	1.51	70%
Bag 2	10	0.33	0.35	105%	7.3	6.1	83%	1.15	1.78	154%
Bag 3	10	0.80	0.65	81%	8.9	6.1	68%	1.40	1.64	117%
ACCEL1	20	1.43	0.88	62%	68.6	36.0	52%	1.59	1.76	111%
RAMP1 unmetered	20	0.22	0.21	94%	4.1	3.6	87%	1.31	2.32	177%
RAMP2 metered	20	0.35	0.32	91%	6.3	5.6	90%	1.26	1.92	153%
RAMP2/RAMP1		1.57			1.53			0.96		

Table 8. Vehicle emission rates by cycle (from bag samples).

	Vehicle		FTP			UC			ACCEL1			RAMP1			RAMP2		
			HC	CO g/mile	NOx	HC	CO g/mile	NOx	HC	CO g/mile	NOx	HC	CO g/mile	NOx	HC	CO g/mile	NOx
1	1992	Taurus	0.23	2.9	0.25	0.19	2.9	0.48	0.89	59.9	1.31	0.10	1.7	0.28	0.13	1.5	0.32
2	1992	Tempo	0.11	0.9	0.25	0.11	1.6	0.32	0.66	70.4	0.12	0.03	0.1	0.19	0.03	0.0	0.42
3	1992	Granada	0.20	4.1	0.36	0.20	4.2	0.29	0.91	54.4	0.43	0.06	1.3	0.13	0.06	1.3	0.20
4	1992	Accord	0.17	2.0	0.25	0.17	2.9	0.27	0.82	79.1	0.32	0.06	1.0	0.10	0.07	1.6	0.20
5	1992	Astrovan	0.90	12.5	1.15	0.69	6.5	1.51	3.07	105.6	2.03	0.38	7.3	1.23	0.54	12.1	1.24
6	1982	Celica	1.31	16.6	0.50	1.32	16.7	0.84	2.51	23.0	3.56	0.74	9.7	0.77	0.97	14.3	0.94
7	1976	Monarch	1.24	27.5	4.20	0.76	20.4	5.97	0.45	24.9	5.77	0.21	6.3	7.94	0.27	7.4	6.69
8	1989	Sedanville	0.32	2.1	0.63	0.39	9.4	0.68	1.44	88.4	1.01	0.18	3.1	0.74	0.38	7.1	0.82
9	1992	Lumina	0.42	4.8	0.34	0.50	12.3	0.20	2.16	139.2	0.12	0.24	6.1	0.19	0.38	7.3	0.21
10	1989	Civic	0.76	7.2	1.50	0.43	8.4	1.66	1.42	40.8	1.31	0.25	4.3	1.60	0.70	10.2	1.54
	Average		0.57	8.0	0.94	0.48	8.5	1.22	1.43	68.6	1.59	0.22	4.1	1.31	0.35	6.3	1.26

Figure 3. Test cycle emission rates (from bag samples) for fuel injected and carbureted vehicles.

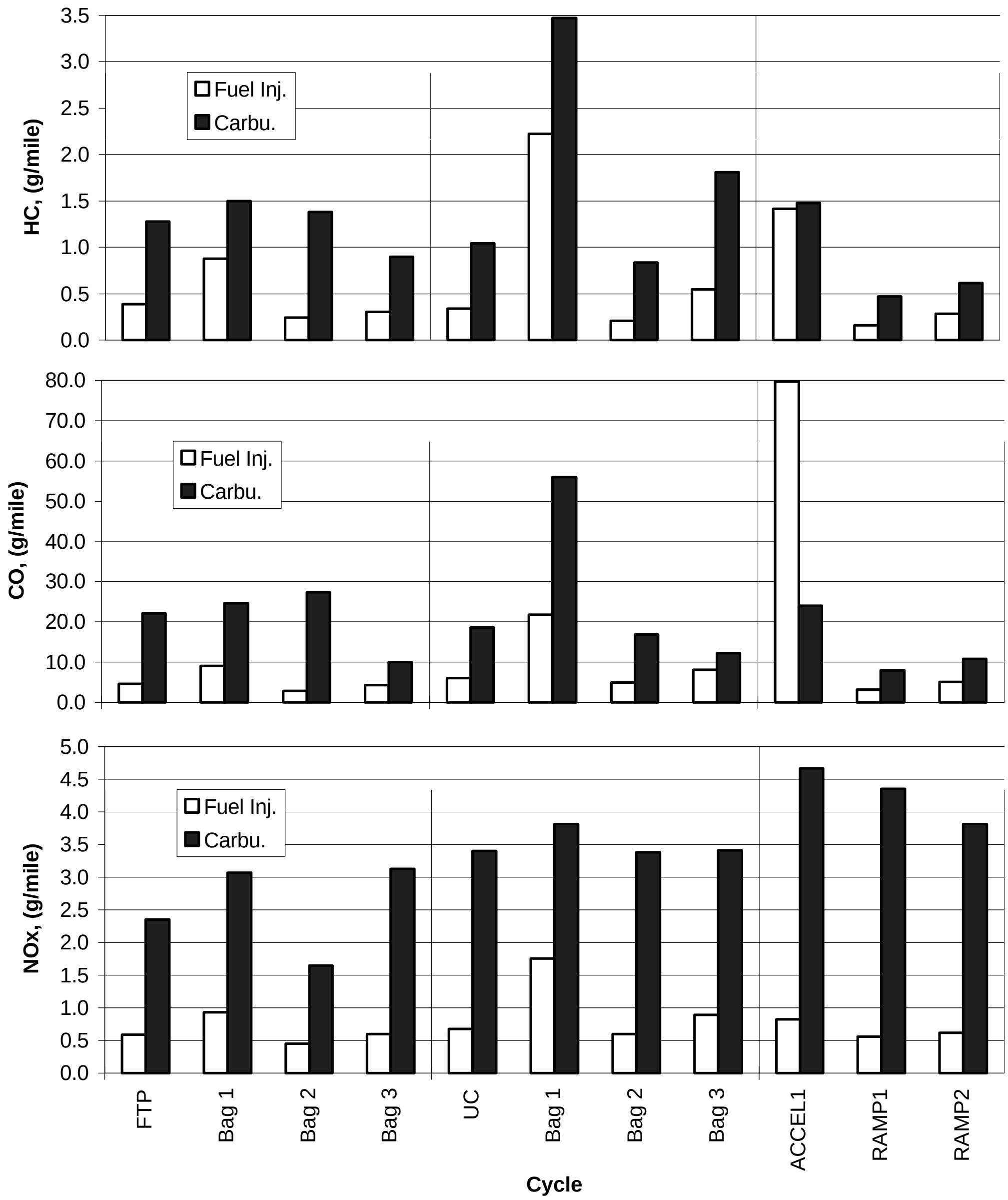


Figure 4. Total emissions by mode for RAMP1 (unmetered) and RAMP2 (metered)cycles.

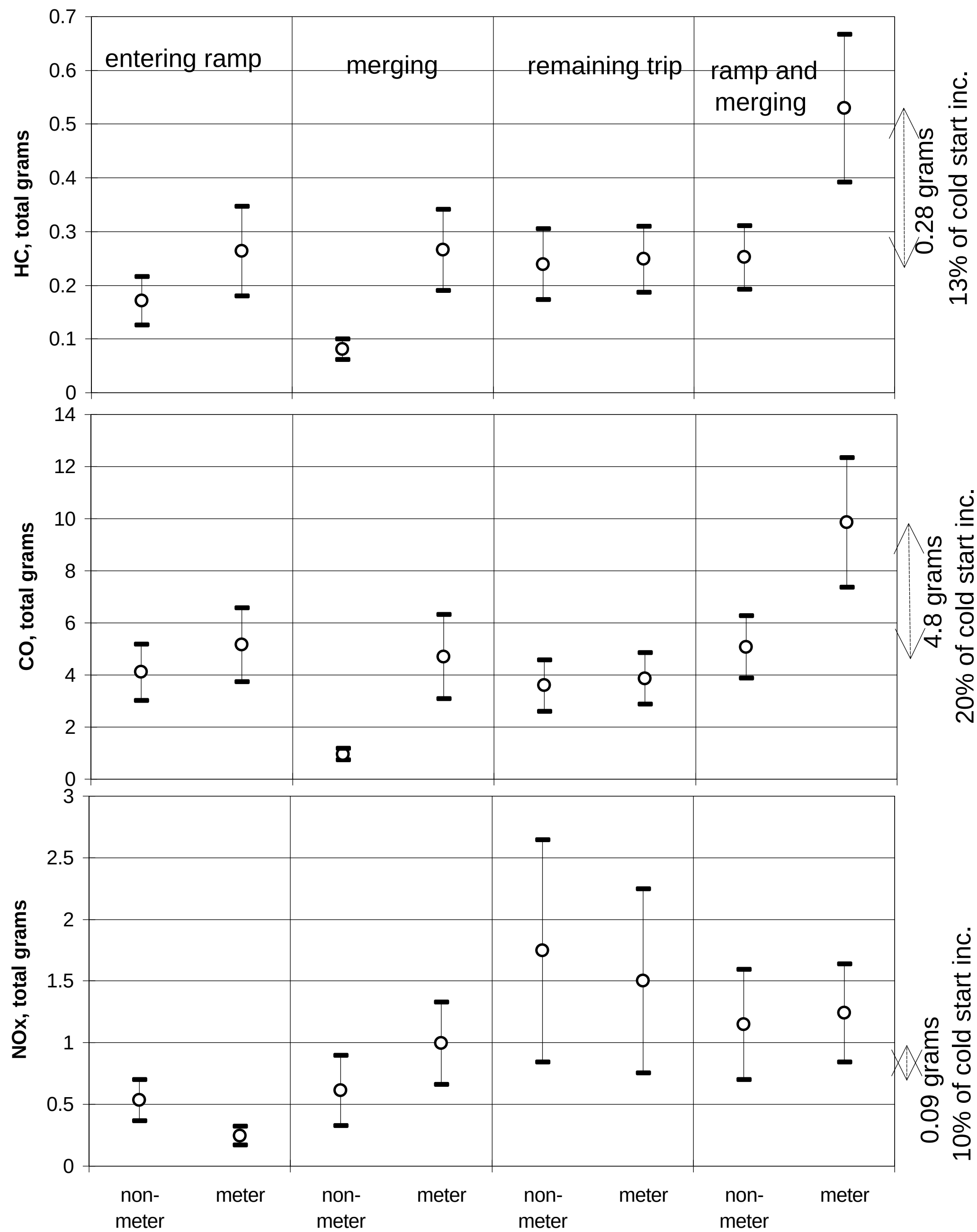


Table 9. Speed enhancement required to break even at given trip lengths and increments due to ramp metering (using current speed correction factors).

				miles	miles	miles
Trip Length				3.0	4.3	8.6
Speed enhancement require to reduce:				MPH	MPH	MPH
0.28 grams of HC		from		35.2	39.5	44.2
		to		52.0	52.0	52.0
		increment		16.8	12.5	7.8
4.8 grams of CO	from		24.3	27.0	31.4	
		to		42.8	42.8	42.8
		increment		18.5	15.8	11.4
0.09 grams of NO_x		from		25.6	26.6	28.0
		to		32.0	32.0	32.0
		increment		6.4	5.4	4.0

CONCLUSIONS

High occupancy vehicles (HOVs), while operating in hilly terrain, may have a lesser effect on improving air quality than has been commonly assumed. Although, other potential beneficial effects of HOV lanes were not considered in this analysis, such as reduced traffic congestion. It is necessary to develop dynamometer driving patterns that account for grade to develop a more definitive emission rates, including NO_x, comprising this additional loads. Optimally, a fleet of vehicles with different weight, power and aerodynamic properties representative of the current vehicle population could be tested.

Although this study was limited to a single ramp, with relatively high merging speed, the current data highlight the potential incremental emissions due to ramp metering at medium to high speeds. It is unlikely that ramp metering offers air quality benefits unless there is an improvement of traffic speeds on the order of 8 MPH from 44 MPH to 52 MPH on long trips (8.6 miles) for hydrocarbons. For CO the traffic should be enhanced from 31 MPH to 43 MPH on long trips. For the case of NO_x it is unlikely that an improvement is achieved under such conditions, since the lowest emissions for NO_x occur at 32 MPH. It is important to account for these additional emissions in the current emissions inventory, and may be 10% to 20% of the incremental cold start emissions.

An additional potential condition that may increase emissions is ramp design, especially those with grades that may impose an additional load on the engine in combination with the ramp metering. Other factors that may promote emissions are short merging lengths. Future research should be directed at characterizing the activity of full ramps and main traffic. Using video processing with one or more synchronized cameras may facilitate the assessment of the full activity of vehicles entering the ramp under different traffic conditions. Chase car data may complement the information by providing a continuous speed profile under different traffic conditions, while vehicle counters may help define the hourly distribution of vehicle flow.

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DISCLAIMER

The contents of this paper/report and the authors' findings do not necessarily reflect the views and policies of the California Air Resources Board. The mention of contractors and commercial products is not to be constructed as either an actual or implied endorsement of such individual products.

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